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GROWTH OF SOYBEAN AND POTATO AT HIGH CO_2 PARTIAL PRESSURES

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ABSTRACT

Soybean and potato plants were grown in controlled environments at carbon dioxide (CO_2) partial pressures ranging from 0.05 to 1.00 kPa. The highest yields of edible biomass occurred at 0.10 kPa for both species, with higher CO_2 levels being supraoptimal, but not injurious to the plants. Stomatal conductance rates of upper canopy leaves were lowest at 0.10 kPa CO_2, while conductance rates at 0.50 and 1.00 kPa were significantly greater than 0.10 kPa. Total water use by the plants was greatest at the highest CO_2 pressures (*i.e.* 0.50 and 1.00 kPa); consequently, water use efficiencies (biomass produced / water used) were low at the highest CO_2 pressures. Based on previous CO_2 studies in the literature, the increased conductance and water use at the highest CO_2 pressures were surprising and pose interesting challenges for managing plants in a CELSS, where CO_2 pressures may exceed optimal levels.

INTRODUCTION

In recent years numerous studies have been conducted to examine the effect of carbon dioxide (CO_2) concentration (partial pressure) on plant growth and development /5/. Typically these studies were oriented toward studying CO_2 effects on plant growth in field settings, but some were conducted in controlled environments with CO_2 treatments maintained for the entire life cycle of plants. These latter studies are useful for assessing the use of plants in a Controlled Ecological Life Support System, or CELSS, and have included CELSS candidate crops such as wheat /3, 6/, potato /13, 14/, soybean /1, 2/, and lettuce /8/. Since many CO_2 studies suggest that plant photosynthetic rates are saturated near 0.10 to 0.15 kPa (1000 to 1500 ppm at sea level /3, 4/), and since maintaining very high CO_2 in controlled environments can be difficult, few studies have examined the effects of CO_2 partial pressures greater than 0.20 kPa. If direct atmospheric exchange is maintained between plant and human habitats in a tightly sealed life support system, CO_2 partial pressures likely will be elevated beyond 0.20 kPa. Cabin atmosphere data from the US Skylab mission showed that CO_2 pressures ranged from 0.20 to 0.60 kPa /12/, while CO_2 on the Mir space station routinely ranges from 0.30 to 0.50 kPa, with some episodes exceeding 1.00 kPa (V. Polyakov, cosmonaut, personal communication). We report here on studies in which soybean and potato plants were grown through their entire life cycle at CO_2 partial pressures ranging from 0.05 to 1.00 kPa. The objective was to determine what effects, if any, CO_2 concentrations similar to those encountered in space life support systems will have on plants.

MATERIALS AND METHODS

Testing included soybean (*Glycine max* (L.) Merr.) cvs. McCall and Pixie and potato (*Solanum tuberosum* L.) cvs. Norland and Denali. Soybeans were started from seed and potato plants from plantlets propagated *in vitro* /14/. All studies were conducted in controlled environment growth chambers using fluorescent (Vita-Lite) lamps to maintain 300 μmol m^{-2} s^{-1} photosynthetic photon flux (PPF) with a 12-h photoperiod. Temperatures were maintained at 26°C (day) / 20°C (night) for soybean and 20°C (day) / 16°C (night) for potato. Plants were grown hydroponically in 0.25 m^2 culture trays using a nutrient film technique with a modified, 1/2 strength Hoagland solution with nitrate as the sole source of nitrogen /7/.

Carbon dioxide (CO_2) treatments were provided by adding CO_2 to the chamber atmosphere to maintain 0.05, 0.10, 0.20, and 0.50 kPa partial pressure (500, 1,000, 2,000, and 5,000 ppm) for soybean studies and 0.05, 0.10, 0.50, and 1.00 kPa (500, 1,000, 5,000, and 10,000 ppm) for potato studies. All studies were conducted at Kennnedy Space Center, FL, USA, which is situated at sea level with an atmospheric pressure of approximately

101 kPa. CO_2 levels were monitored and controlled with an infrared gas analyzer (Anarad model AR-200), and occasionally checked with gas chromatography using a thermal conductivity detector (Hewlett Packard, 5880).

Throughout growth and development, water use by the plants was tracked by recording the amount of water needed to fill the nutrient solution reservoir to a fixed volume each day. Beginning at approximately 28 days after planting, leaf stomatal conductance was measured each week with a steady-state porometer (Li-Cor model LI-1600). Weekly conductance measurements included 12 leaves for each cultivar of each species. Measurements were taken in the middle of the 12-h photoperiod and used only the most recent, full-expanded leaves in the upper canopy of the plants. To avoid increased CO_2 levels during measurements at 0.05 kPa CO_2, a mask connected to a vacuum pump outside that growth chamber was worn to remove CO_2 from breathing. For all other CO_2 treatments, the control system quickly adjusted to CO_2 added from human breathing by reducing the amount of CO_2 added to hold the set point.

Soybean plants were harvested at 90 days after planting and potato plants at 105 days after planting. All plant materials were oven dried at 70°C for at least 48 hours for dry weight (DW) determination.

RESULTS AND DISCUSSION

Productivity. The highest yields in terms of total plant DW and seed DW for soybean plants occurred at 0.10 kPa for both cultivars, although the differences between CO_2 treatments for cv. Pixie were not significant (Table 1). Increasing the CO_2 beyond 0.10 kPa resulted in slightly reduced yields, indicating that 0.10 kPa CO_2 was close to an optimal level for conditions used in these studies. The highest harvest index, (*i.e.* seed DW / total DW) occurred at the lowest CO_2 pressure, 0.05 kPa, which is consistent with reports in the literature /5/.

TABLE 1. Growth parameters of soybean as infuenced by CO_2 partial pressure and cultivar. Each value is a mean of two replicates (trays) ± SE measured at 90 days after planting.

		CO_2 Partial Pressure (kPa)			
Parameter	Cultivar	0.05	0.10	0.20	0.50
Seed DW[1]	McCall	166 ± 14	197 ± 3	174 ± 10	154 ± 8
	Pixie	79 ± 10	83 ± 10	64 ± 10	68 ± 3
Stem DW	McCall	45 ± 3	64 ± 3	68 ± 1	57 ± 1
	Pixie	23 ± 2	33 ± 1	42 ± 9	26 ± 1
Leaf DW	McCall	73 ± 4	87 ± 5	105 ± 01	113 ± 3
	Pixie	56 ± 5	70 ± 7	76 ± 11	69 ± 5
Pod DW	McCall	63 ± 6	74 ± 2	65 ± 4	60 ± 3
	Pixie	27 ± 4	29 ± 5	22 ± 4	23 ± 2
Root DW	McCall	14 ± 1	20 ± 1	18 ± 2	17 ± 1
	Pixie	12 ± 2	18 ± 2	13 ± 1	11 ± 1
Total DW	McCall	360 ± 27	442 ± 13	408 ± 05	400 ± 13
	Pixie	197 ± 22	233 ± 25	217 ± 35	198 ± 01
HI[2]	McCall	45 ± 0	45 ± 1	39 ± 0	38 ± 0
	Pixie	39 ± 0	36 ± 1	28 ± 2	34 ± 3

[1] DW = dry weight in grams per tray; each tray occupied approximately 0.3 m^2.
[2] HI = harvest index (seed DW/total DW).

Potatoes also showed the highest edible (tuber) yield at 0.10 kPa CO_2. The highest total plant DW for cv. Denali occurred at 0.10 kPa, while the highest total DW for cv. Norland occurred at 1.00 kPa. Except for cv. Norland at 0.05 kPa, differences in total DW between treatments were not significant. The highest harvest index (tuber to total DW ratio) occurred at 0.10 kPa for cv. Denali, and at 0.10 and 0.50 kPa for cv. Norland.

Thus, as with soybean, the optimal CO_2 level for potato production under these conditions appeared to be near 0.10 kPa, although it is noteworthy that yields for both cultivars did not decrease significantly as CO_2 was increased further to 0.50 and 1.00 kPa.

For both species, growth and development appeared to be normal in all respects, with the possible exception of some leaf chlorosis on soybean plants at 0.50 kPa CO_2. In addition, the occurrence of intumescence (oedema) injury /9/ appeared to increase on potato cv. Denali leaves with increased CO_2, but this was not quantified.

TABLE 2. Growth parameters of potato as influenced by CO_2 partial pressure and cultivar. Each value is a mean of two replicates (trays) ± SE measured at 105 days after planting.

		CO_2 Partial Pressure (kPa)			
Parameter	Cultivar	0.05	0.10	0.50	1.00
Shoot DW[1]	Denali	132 ± 31	131 ± 15	156 ± 11	177 ± 13
	Norland	84 ± 18	107 ± 14	95 ± 08	171 ± 17
Tuber DW	Denali	517 ± 22	579 ± 23	441 ± 24	517 ± 71
	Norland	239 ± 07	461 ± 65	414 ± 25	440 ± 77
Total DW	Denali	665 ± 53	720 ± 40	604 ± 36	702 ± 84
	Norland	326 ± 25	573 ± 80	512 ± 33	623 ± 93
HI[2]	Denali	78 ± 3	82 ± 2	73 ± 0	74 ± 2
	Norland	74 ± 4	82 ± 1	81 ± 1	71 ± 2

[1] DW = dry weight in grams per tray; each tray occupied approximately 0.3 m^2. Shoot includes leaves and stems.
[2] HI = harvest index (tuber DW/total DW).

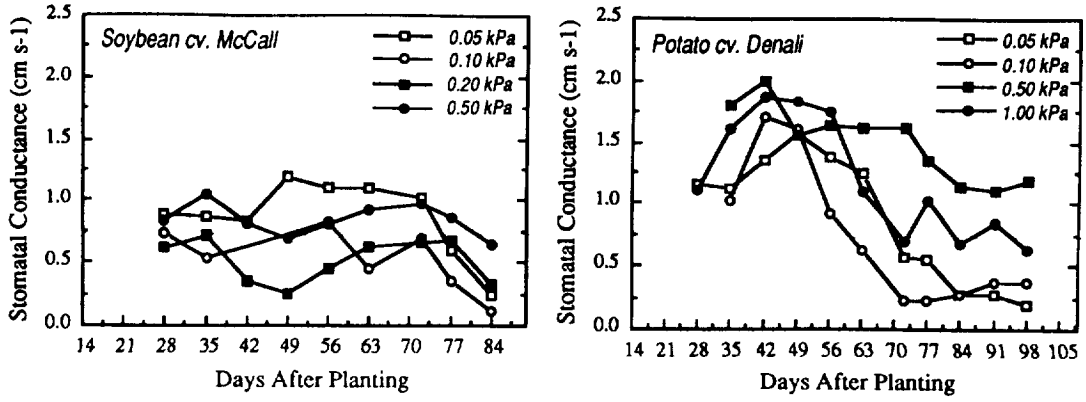

Fig. 1. Effect of CO_2 partial pressure on stomatal conductance of upper canopy leaves of soybean and potato throughout growth. All measurements were taken in the middle of a 12-hr light period.

Water relations. Stomatal conductance rates from upper canopy leaves of soybean (cv. McCall) and potato (cv. Denali) over time for the different CO_2 treatments are shown in Fig. 1 a and b. Early in growth, the highest conductance occurred at the lowest CO_2 level, 0.05 kPa, while the lowest rates occurred at 0.10 kPa for potato and 0.20 kPa for soybean. Stomatal conductance rates at 0.50 kPa (soybean and potato) and 1.00 kPa (potato) were higher than 0.10 kPa, and as high as or higher than at 0.05 kPa. The relative rankings between these treatments generally persisted throughout growth for both species. The highest water use for both species occurred at the highest CO_2 partial pressures (Table 3 a and b). This, combined with the lack of increased yield (relative to 0.10 kPa), resulted in reduced water use efficiency for both species at the highest CO_2 pressures (Table 3).

The decrease in stomatal conductance as CO_2 was increased from 0.05 to 0.10 kPa is consistent with reports in the literature /5, 10/, but the increased conductance and water use as CO_2 was increased from 0.10 to 0.50 and 1.00 kPa CO_2 was unexpected and runs counter to the notion that high CO_2 tends to close stomata /5, 10/. Yet reports exist suggesting that very high CO_2 partial pressures can reverse the tendency of stomata to close near 0.10 kPa /11/, and our findings support this observation.

TABLE 3. Effect of CO_2 partial pressure on plant growth and water use. Measurements taken at 90 days after planting for soybean and 105 days after planting for potato.

Crop	CO_2 (kPa)	Total Dry Weight (kg)	Total Water Use (kg)	Water Use Efficiency (g kg^{-1})
Soybean	0.05	2.04	845	2.42
	0.10	2.49	822	3.03
	0.20	2.24	879	2.54
	0.50	2.27	1194	1.91
Potato	0.05	3.25	483	6.73
	0.10	4.02	573	7.02
	0.50	3.66	916	4.00
	1.00	4.04	910	4.44

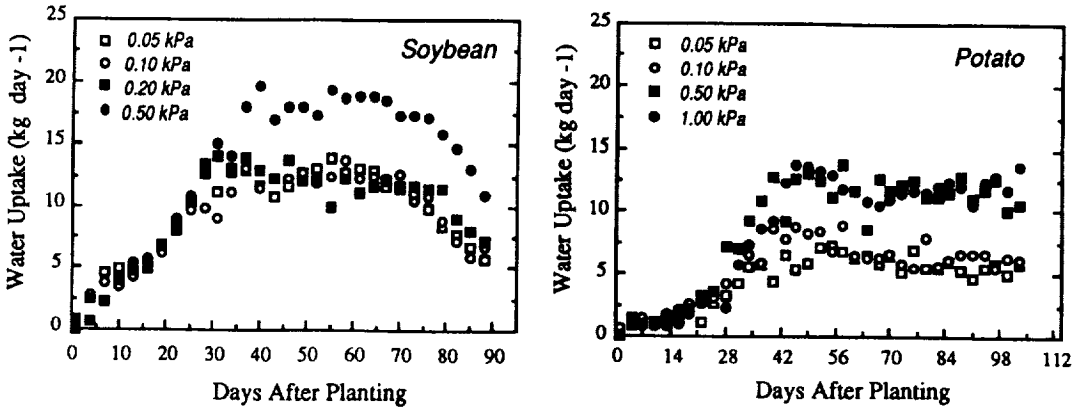

Fig. 2. The effect of CO_2 partial pressure on plant water use over time. Each study had eight 0.3 m^2 culture trays, comprised of two cultivars at two planting densities.

With regard to growing crops in a CELSS, these findings suggest that optimal growth with minimal water use for soybean and potato should occur near 0.10 kPa CO_2. Carbon dioxide partial pressures of 0.20 kPa or higher may result in a slight decrease in yield, particularly with soybean, while very high CO_2 pressures (0.50 kPa to 1.00 kPa) may cause an increase in water use for both species. Such an increase in water use at the higher CO_2 pressures might be used advantageously if the plants were incorporated into a waste treatment scenario. For example, very high CO_2 levels might be used to speed transpiration and hence production of clean, condensable water while only causing a slight reduction in edible biomass. Whether the same trends of water use and yield in response to CO_2 partial pressure would occur under different environmental conditions, *e.g.* different humidities or different irradiance, should be studied further. Environmental studies with potato showed that CO_2 enrichment to 0.10 kPa was beneficial with moderate irradiance and short photoperiods, but less beneficial at higher irradiance, and even damaging at high irradiance in combination with continuous light /14/.

SUMMARY

Optimal growth and yield for soybean and potato plants grown hydroponically in controlled environment occurred near 0.10 kPa CO_2. Increasing the CO_2 beyond this was not injurious to the plants but resulted in a slight decrease or no improvement in total or edible biomass production. Raising the CO_2 from 0.05 to 0.10 kPa reduced stomatal conductance and increased water use efficiency for both species, but raising the CO_2 to 0.50 or 1.00 kPa resulted in increased stomatal conductance, increased water use, and decreased water use efficiency (relative to 0.10 kPa). The results suggest that at moderate irradiance, soybeans and potatoes should fare well under very high CO_2 partial pressures, similar to what might be encountered in life support habitats in space, but that very high CO_2 levels may result in high rates of canopy transpiration and the production of condensable, potable water from the plants.

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